Narrow heat flux widths and tungsten: SOLPS studies of the possible impact on ITER divertor operation

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Abstract. The paper presents results of a first analysis of the divertor performance during the L-H transition in ITER. The integrated model consists of the SOLPS4.3 code suite for the SOL and divertor, and the ASTRA code for the core and pedestal regions. The results of SOLPS4.3 are parameterized and used as the boundary conditions for ASTRA, ensuring a consistent description of the plasma core and the edge. Boundary conditions switch from those for wide (L-mode) to narrow (H-mode) SOL once the transition criterion is met. The results show that, for conditions for which a full-power operational space with acceptable power loading of the targets exists, a transition from the initial L-mode operation to H-mode can be found for the same assumptions, i.e. the full-power H-mode regime is accessible.

1. Introduction

The ITER Organization has recently been considering the use of a full tungsten (W) divertor from the beginning of operation through the end of first DT campaign [1]. There are, however, several potential issues facing full power, steady state operation using W rather than carbon (C). Tungsten is a high-Z material with a very low acceptable concentration in the core of a burning plasma. Therefore, the target erosion must be kept to low values, even during transients, restricting the range of acceptable parameters of the divertor plasma and thus impacting the achievable operational window for the whole machine. In this paper we address one of these issues by employing the SOLPS4.3 plasma boundary code suite [2], providing consistent boundary conditions to the ASTRA code and thus forming an integrated model of the whole ITER plasma [3].

Recent experimental observations of a very small scrape-off layer (SOL) width for energy flow, λ_q, in the inter-ELM H-mode [4, 5], followed by a paper proposing a possible formation mechanism for such a feature [6], have raised a concern for the consequences for target heat loading if such small λ_q were to occur in ITER. Multi-machine scaling from these experimental measurements [7] is in good agreement with the dependences predicted in the model of [6] and suggests a dependence essentially only on inverse plasma current, implying λ_q ~1 mm in ITER in high performance H-mode. Direct extrapolation to this extremely low value, however, seems unlikely since it implies SOL gradients above the ballooning limit (see discussion later in the text). Previous simulations [8] using the same integrated model for C at the divertor strike points have shown that because of the energy dissipation by impurity radiation in the divertor, it is possible to maintain the peak divertor power load, q_{pk} in ITER at an acceptable level even if λ_q were reduced down to 1.2 mm instead of the 3.6 mm resulting from current transport assumptions. In those results, partial detachment of the divertor counteracts the effect of narrowing the SOL and an operational window for the full-power H-mode would exist even if the power SOL became that narrow. However, the reduced radial transport in the small λ_q case leads to relatively high separatrix density, $n_{e\_sep} \sim 0.5\ n_G$ (n_G is the Greenwald density). Whereas achieving such a high n_{e_sep} should not be a problem during the H-mode burn phase in ITER, the H-mode needs to be accessible, which requires a sufficiently low L-H transition power threshold, i.e. a sufficiently low n_{e_sep}. The aim of this paper is to show that a transition from the initial L-mode operation to H-mode can be found for the same assumptions for which the full-power H-mode regime is sustainable for the case of DT plasma, and to show that it is also possible for D plasma. For simplicity, we consider here a carbon divertor, assuming that the similarity of C divertor performance to that of the W divertor with Ne impurity seeding found in [9] translates to the present divertor configuration. Unless stated otherwise, all the results apply to DT plasma.

Section 2 shows the results of the analysis of the operational space of the ITER divertor with reduced λ_q, expanding the results of [8] towards the lower SOL input power, P_{SOL} relevant to the L-H transition phase. These results are then approximated as scaling relations and used as boundary conditions for the integrated model describing, in a simplified way, the L-H transition. The integrated model is described in section 3 and the results are presented in section 4. Section 5 summarizes the main findings.

2. Narrow SOL: extended power scan

For this analysis we produced several density scans with SOLPS4.3, varying the SOL input power (P_{SOL} = 60, 40, 30, and 20 MW) and radial transport (λ_q = 3.6 and 1.6 mm). As discussed in [8], a SOL narrower than this (λ_q = 1.2 mm) is unlikely to occur since the radial pressure gradients in the SOL would then exceed the ballooning limit, i.e. the radial profiles in the SOL would be steeper than those inside the pedestal. Therefore, here we give results for the less extreme case λ_q = 1.6 mm and will use an extrapolation to 1.2 mm in the subsequent sections. In this study we focus on the L-H transition which should occur early in the discharge and do not yet optimize the fusion power in the developed H-mode by adjusting the core fuelling. (The P_{SOL} range from 60 to 120 MW with high fusion power with this optimization has already been explored [10, 8] and those results are included in the scalings).

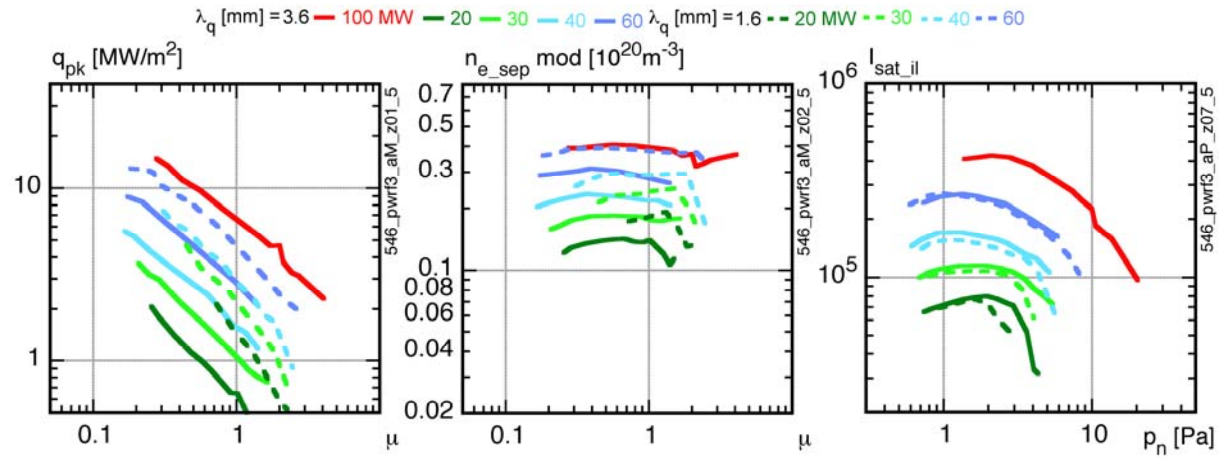

Fig. 1. Left to right: peak power on the target and separatrix density vs. normalized divertor neutral pressure and ion saturation current to the inner target vs. non-normalized neutral pressure in the divertor (see text).

Fig. 1 shows the resulting dependence of q_{pk} (parameter limited by the technical heat handling capability of the targets) and n_{e_sep} (boundary condition for the core) on the normalized neutral pressure in the divertor μ, as well as the total ion saturation current to the inner target I_{sat_il} vs. the neutral pressure p_n. Parameter μ is normalized so as to reach 1 at imminent detachment of the inner target (which detaches first), which is in turn related to the roll-over of I_{sat} [10].

As expected, at given μ both q_{pk} and n_{e_sep} decrease as P_{SOL} decreases. During and after the transition, the ratio of P_{SOL} to P_{LH} will tend to decrease because of the increase of n_{e_sep} due to the SOL narrowing in H-mode, and to increase because of the increase of input power (both auxiliary power and, in the case of DT, fusion power). Since this picture involves both the edge and core plasma, a quantitative study can only be done with an integrated model that treats the core and edge in a consistent way, as described in the next section.

3. Integrated transport model

The transport model used here is a further development of the model described in [3]. A parameterisation of the results of the SOL and divertor modelling is applied to obtain the boundary conditions at the separatrix for a 1D transport model in the core. The SOLPS4.3 results are represented by scalings relating the core output (power and ion particle fluxes), together with extra controls such as pumping speed and gas puffing rate, to the resulting separatrix densities, temperatures and neutral influx (and also q_{pk}). This approach yields parameters of the core plasma consistent with the edge and allows application of constraints stemming from the engineering limitations such as q_{pk} and particle throughput in the pumping system.

The model was originally developed and tested for H-mode plasmas [3] and found there to yield profiles similar to the JET profiles for H-mode conditions. It employs the MMM transport model with an empirical scheme to model the transport reduction in the pedestal region, depending on the shear of the ExB velocity and magnetic field (see [3] for the details). In the present paper, we use different transport coefficients and boundary conditions for the L-mode and the H-mode and switch from L- to H-mode when the L-H power threshold is exceeded. A similar criterion is applied for the H-L back transition.

The model of [3] with transport reduction and subsequent limit on the pressure gradient in the pedestal together with the SOLPS4.3 data for the narrow SOL represent the H-mode. For the L-mode, the boundary conditions are taken from the “standard” SOLPS4.3 modelling runs [10], and the MMM energy transport coefficients are multiplied by a factor of 3 so as to obtain an energy confinement time approximately equal to L-mode scaling [11]. Because the pressure gradient near the edge is then below the criterion for stabilization by shear, no transport reduction is applied, so that no pedestal is produced and the ballooning limit is not attained. An inward particle pinch ($v = -2C\,D\,r/a^2$) with pinch coefficient $C = 1.0$ is added to obtain a reasonably peaked density profile in L-mode ($n(0)/\langle n\rangle \sim 1.5$) similar to that of present-day experiments. Since the existence and nature of this pinch in present H-mode experiments is still unclear and its extrapolation to ITER H-mode even more uncertain, we consider both C=0 and C=0.5 in the H-mode, similarly to [12]. (Note, however, that no pinch is required, i.e. C=0, for our model to reproduce well the H-mode density profiles in JET [3].) For all simulations, the particle transport coefficient D is taken as $0.1*(\chi_e+\chi_i)$ [3] and the Ware pinch is included.

For the L-H transition threshold power we use the scaling in [13] (i.e. $P_{LH} \propto \langle n_e\rangle^{0.717}$, as given there, without isotope effect). If a proportionality to isotope mass exists in addition, the figures here will be lower by 25% for the 50-50 DT mixture cases. In some experiments, it has been observed that the ratio of the power at the back transition to that at the forward transition can be as low as 1/2. Accordingly, such a hysteresis is implemented in the model, and the value of the ratio necessary to remain in H-mode is determined for each case. This model thus takes into account the effects of variation of plasma density and power across the pedestal and appears reasonable for initial explorations. Naturally, in order to study the detail of the L-H transitions, one needs a more refined model. In any case, this model must include the proper boundary conditions describing the change of the plasma parameters at the separatrix with a modification of the SOL transport by the L-H transition.

All the simulations described here start from the well-developed L-mode obtained with the above transport assumptions. Fuelling as described in [3] is adjusted to obtain an average density of $\langle n_e \rangle \geq 0.5 \cdot 10^{20}$ m^{-3}, sufficient to limit beam shine-through, and 30 MW heating power is applied, well below the L-H transition threshold power. At a given point in time, the beam power is ramped up to 70 MW over a 10 s time period. As soon as the power crossing the separatrix exceeds the L-H power threshold, the energy transport coefficients are reduced to the MMM value (from thrice that value in L-mode), transport reduction by shear is applied, and the resulting pressure profile is restricted to the ballooning limit. At the same time, the particle pinch coefficient switches from the L-mode value (1.0) to the desired H-mode value (0.0 or 0.5). During the H-mode, the core fuelling remains adjusted to produce $\langle n_e \rangle \geq 0.5 \cdot 10^{20}$ m^{-3}, but $\langle n_e \rangle$ will rise above this value whenever the edge density from the boundary conditions is higher (narrow λ_q, or extra puffing required to maintain q_{pk} at the allowed level).

4. Accessibility of the operational window

As shown in [8], an operational window for the H-mode in ITER exists even with reduced λ_q. The next concern is the power loading on the targets during the L-H transition in the early phases of discharges when the plasma density may have to be reduced in order to lower P_{LH}. It can be seen from Fig. 1 that low n_{e_sep} in the L-mode appears naturally, favouring the initial L-H transition. If after the transition n_{e_sep} increases, causing a corresponding increase of the pedestal density, P_{SOL} can become lower than P_{LH} and the plasma would switch back to the L-mode – unless the reduction of P_{SOL} brings n_{e_sep} back to a lower value, Fig. 1. In order to explore the relative importance of these factors, we follow the strategy described below.

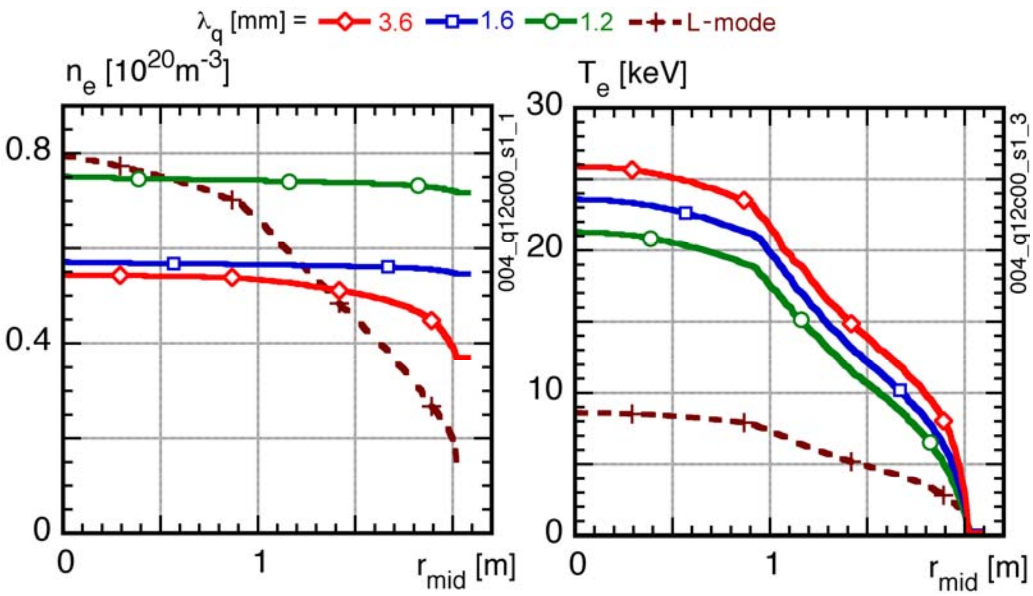

Fig. 2. Radial profiles of plasma density and temperature in L-mode just before the ramp-up of the heating power, and in steady H-mode for λ_q=3.6, 1.6, and 1.2 mm.

First, the gas puffing rate (and hence p_n) is dynamically adjusted if necessary so as to keep q_{pk} below the specified limit as the external power (and alpha particle power for the case of DT) is increased. This procedure keeps the lowest possible n_{e_sep} at every moment, yielding the optimum with respect to P_{LH}. We start from a stationary L-mode solution with a heating power of 30 MW, resulting in the typical core profiles shown in Fig. 2. Then, at some point, the heating power is gradually increased to 70 MW and, since P_{SOL} is then larger than P_{LH} for both the DT and D cases the plasma switches to H-mode. This transition is assumed to occur immediately (the timescale of the transport barrier formation is much shorter than τ_E [14]), resulting in a step-wise change of the transport coefficients and boundary conditions. The plasma evolves further; it becomes hotter and the fusion power rises as well in the DT plasma cases. (In this particular study of the vicinity of the L-H transition, no extra core fuelling is applied to increase the fusion power – therefore the resulting fusion gain Q is 2 to 4 depending on λ_q, lower than that expected in the normal operation.) If at some point along this evolution the criterion $P_{SOL} < 0.5P_{LH}$ (hysteresis) is met, then the plasma transport and boundary conditions switch back to the L-mode values.

For the H-mode, we vary λ_q in the H-mode, using either the standard 3.6, or 1.6, or 1.2 mm [8]. The resulting profiles are shown in Fig. 2. The pinch velocity is also varied, setting C to either 0 or 0.5.

The resulting traces of the discharge evolution for C = 0 and three values of λ_q, with q_{pk} kept below 10 MW/m^2 (engineering limit for steady state target power handling), are shown in Figs. 3, 4. Fig. 3 shows the evolution of the L-H "transition margin" $\eta_{LH}= P_{SOL}/P_{LH}$ and μ which characterizes the detachment state. For all the cases shown here, the core plasma switches to H-mode and stays there with a margin ($\eta_{LH} \geq 1.5$) – probably sufficient for a high quality H-mode with Type I ELMs [14] even with low fusion power. The detachment state of the divertor is also consistent with a good H-mode ($\mu < 1$) for the larger values of λ_q, with some margin until λ_q = 1.3 mm is reached (interpolating in Fig. 3). If λ_q falls below this value, the p_n required to keep the $q_{pk} \leq 10$ MW/m^2 becomes so high that the divertor detaches fully ($\mu > 1$) and the core confinement would be expected to degrade [15]. This is similar to

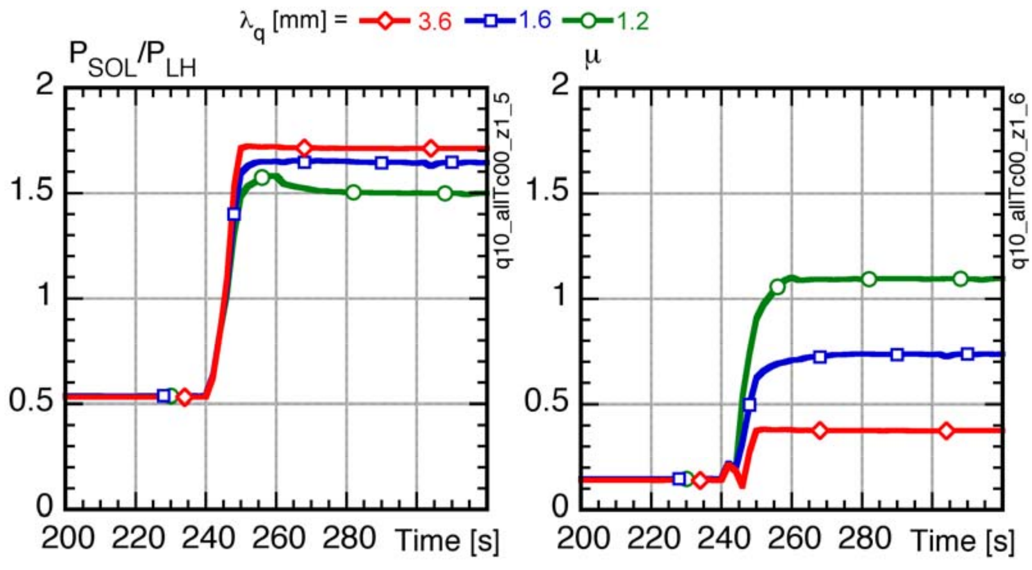

Fig. 3. Evolution of the L-H transition margin $\eta_{LH} = P_{SOL}/P_{LH}$ (left) and the normalized neutral pressure in the divertor μ for λ_q=3.6, 1.6, and 1.2 mm for DT plasma The H-mode switches on at the point where η_{LH} = 1.

the reduction of the operational window observed in [8] for full-power operation of ITER. However, even for these unlikely conditions a remedy can be found, e.g. by permitting the allowable q_{pk} to increase by some 20% – again similar to the conclusions for full power operation in [8].

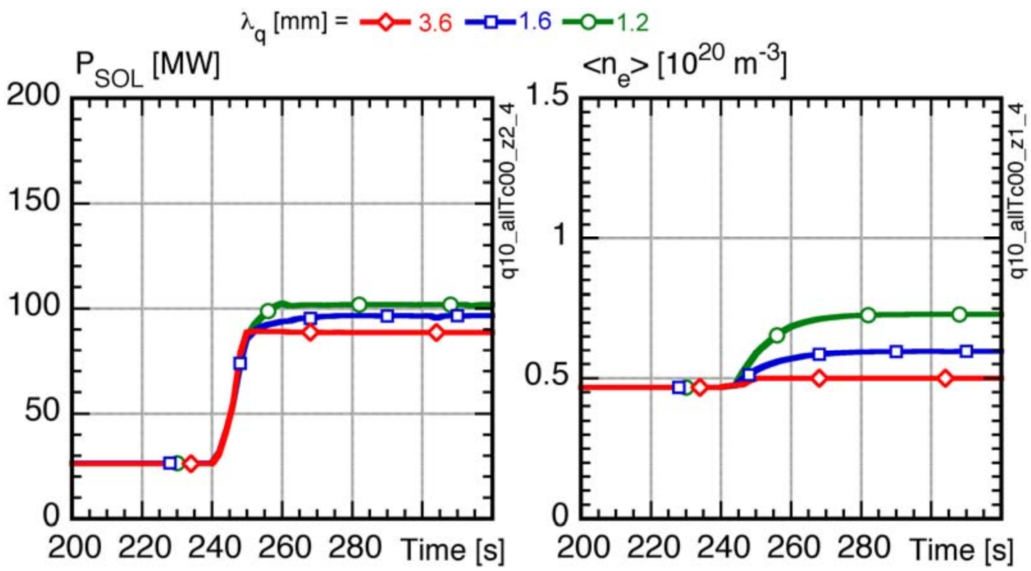

Fig. 4. Evolution of P_{SOL} and $\langle n_e \rangle$ for DT plasma, for the 3 cases of λ_q.

Fig. 4 shows the evolution of P_{SOL} and $\langle n_e \rangle$ for the same case. The H-mode density increases with the reduction of λ_q, consistent with Fig. 1. However, the L-H transition occurs at rather low P_{SOL} ~ 50 MW where the separatrix density even for the narrow SOL is not too high, Fig. 1. The core density changes on the transport time scale, so there is no sharp increase of $\langle n_e \rangle$. Therefore, the transition goes smoothly, with no excursions of P_{LH}, and only a minor excursion of η_{LH} (see Fig. 3).

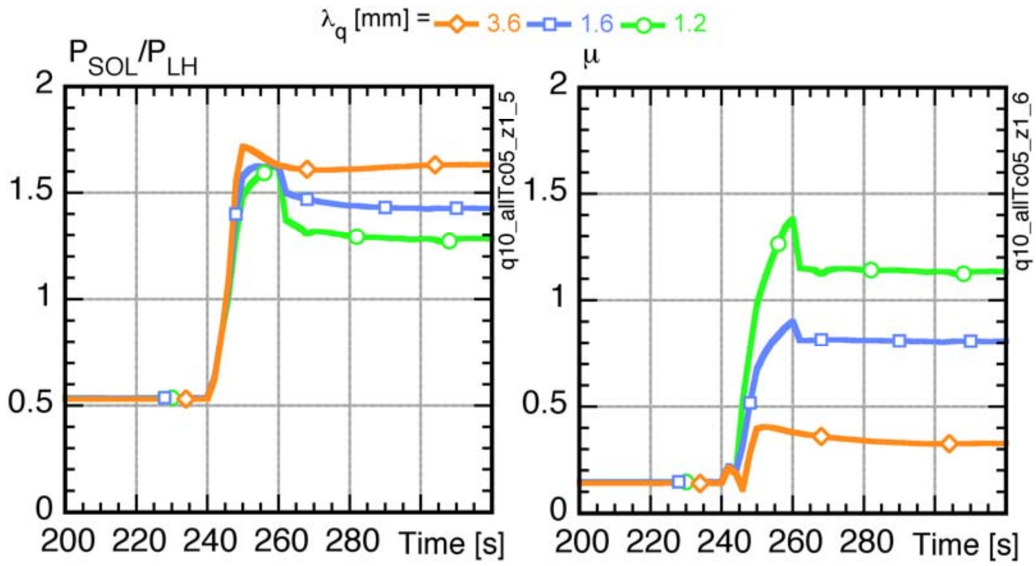

Fig. 5. Traces of η_{LH} and μ for DT plasma, for C = 0.5, $q_{pk} \leq 10$ MW/m^2.

Introduction of an inward pinch, C = 0.5, increases the core density and hence P_{LH} for the same separatrix conditions. In this case (Fig. 5) the L-H transition margin becomes lower, although still $\eta_{LH} > 1.25$, and μ remains essentially unchanged at late times with a brief excursion to higher values just after the transition. In this case, in comparison with the case for C = 0, $\lambda_q > 1.5$ would be required to maintain adequate detachment margin. Other than that, the properties of the L-H transition in ITER show no strong dependence on the particle pinch within the range examined.

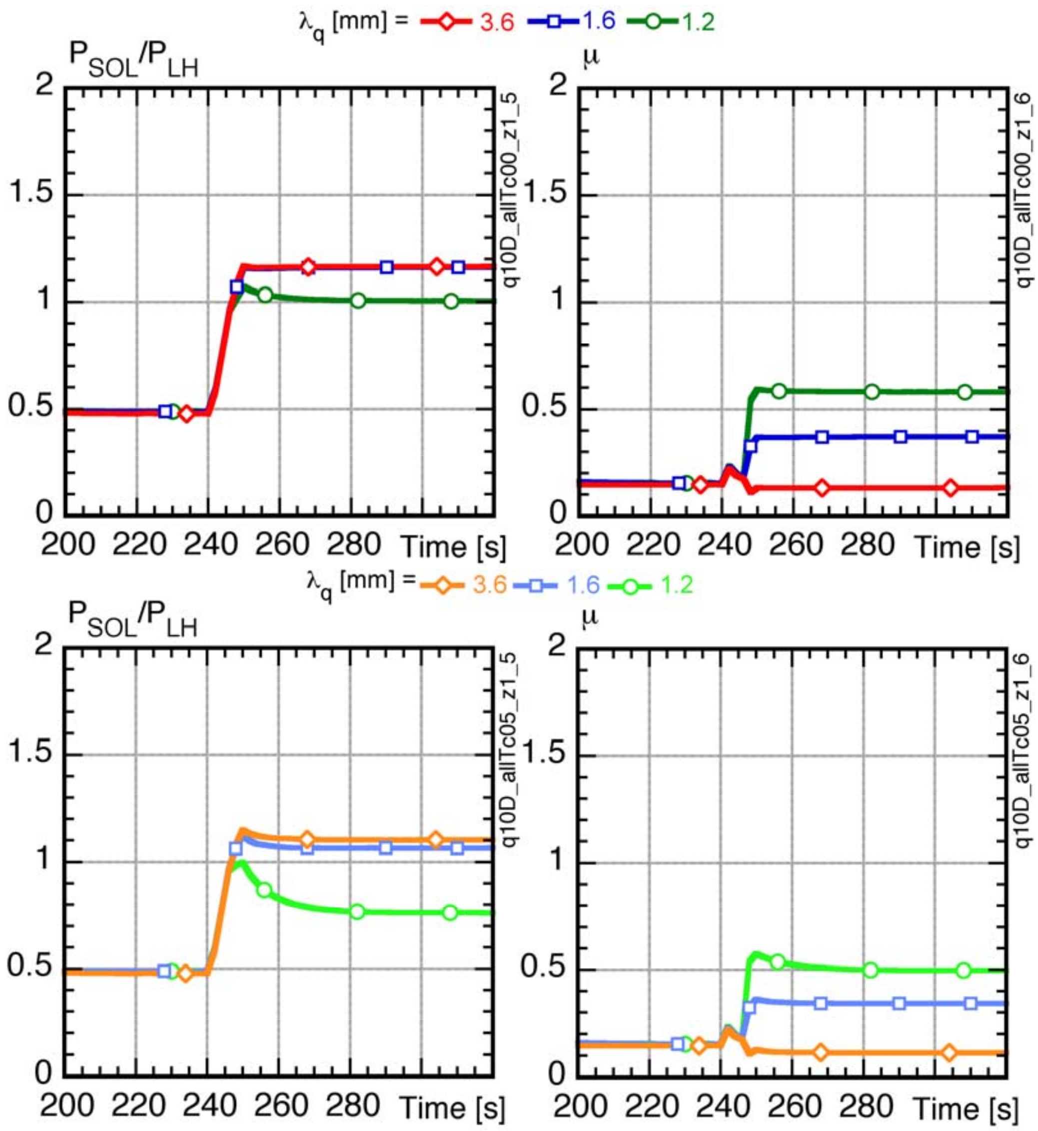

Fig. 6. Traces of η_{LH} and μ for the case of pure D plasma, C = 0 (top) and 0.5 (bottom), $q_{pk} \leq 10\ MW/m^2$.

Results of a similar study for operation with pure D (no fusion power) are given in Fig. 6. One can see that a transition to the H-mode occurs and that the plasma is far from detachment in both L- and H-mode (because there is no fusion power), but the quality of this H-mode will probably be low, $\eta_{LH} < 1.15$ for all options considered.

Even in D plasma (in the absence of fusion power), no back transitions are obtained at zero pinch velocity. For a pinch parameter of 0.5, back transitions do occur if the hysteresis between forward and back transition threshold is not large (e.g. $P_{HL} \sim 0.9\ P_{LH}$, not shown here).

5. Conclusions

The previous study reported in [8] of the operational window for DT plasma in ITER with a carbon divertor and variable SOL power width has been extended to the low power conditions near the L-H transition. The H-mode SOL width has been varied from 3.6 to 1.2 mm, with the finding that the L-H transition should occur even at the higher separatrix densities that prevail if the H-mode λ_q were really as low as the ~1.5 mm. In other words, even if the λ_q reduction in H-mode found in current experiments (and at least one theoretical model) can be extrapolated to ITER operation at high plasma current, the L-H transition is not precluded. A similar conclusion is obtained for the L-H transition in D plasmas but the margin in SOL power relative to the L-H threshold is lower there. On the basis of a previous comparative study of ITER with C and W divertors [10] these results are expected to carry over when a W divertor is used. A further reduction of λ_q, although deemed unlikely on the grounds of stability considerations [8], would require optimization of the operation scenarios to reach a good quality H-mode with a sufficient margin with respect to P_{LH}. In particular, if this very low λ_q had to be accommodated, it might be necessary to permit the allowable q_{pk} to increase by some 20% to avoid full divertor detachment during the L-H transition, as was also the case for full power operation under these conditions [8].

The results show therefore that, for conditions for which a full-power operational space with acceptable power loading of the targets exists, a transition from the initial L-mode operation to H-mode can be found for the same assumptions, i.e. the full-power H-mode regime is accessible. Further simulations for the case of a W divertor are underway.

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